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IMPACT OF THE AIR NOZZLES CONFIGURATION IN THE BIOMASS BOILER ON THE CARBON MONOXIE EMISSION

WPŁYW KONFIGURACJI DYSZ POWIETRZNYCH KOTŁA NA BIOMASĘ NA EMISJĘ TLENKU WĘGLA

A b s t r a c t

The aim of the research was to evaluate possibility to reduce the emission of the carbon monoxide (CO) in the biomass boiler, by application of a newly-designed secondary air supply system. The approach implied the practical tests of the real biomass boiler installation and numerical analyses of chosen optimizing solutions of the secondary air distribution system. Promising modifications have been implemented in the current design and tested. Results of the numerical and experimental studies have been compared and discussed.

Keywords: *straw combustion, CO emission, CFD*

S t r e s z c z e n i e

Celem badań była ocena możliwości redukcji emisji tlenku węgla (CO) w czasie spalania słomy w dedykowanym kotle wsadowym, poprzez modyfikację systemu dystrybucji powietrza wtórnego. Wykonano serię eksperymentów z wykorzystaniem instalacji doświadczalnej kotła, a także analizy numeryczne uwzględniające wybrane rozwiązania optymalizacyjne w zakresie dystrybucji powietrza wtórnego. Rozwiązanie dające obiecujące wyniki obliczeń zaimplementowano w rzeczywistej jednostce. Wyniki analizy numerycznej i prac doświadczalnych zostały porównane i przedyskutowane.

Słowa kluczowe: *spalanie słomy, emisja CO, CFD*

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1. Introduction

The process of lignin-containing cellulosic fuels gasification is similar to classic combustion, but it occurs in case of insufficient amount of oxygen (less than enough for the stoichiometric combustion) [1]. For equivalence ratios below 0.1, the pyrolysis occurs. In such case only a modest fraction of the biomass energy is found in the gaseous product – the rest being in char and oily residues. If the equivalence ratio is between 0.2 and 0.4, the process is called a proper "gasification". Such process is characterised by the highest level of energy transfer to the gas [2].

In case of the biomass boilers, products of the gasification are burned in separated area of the combustion chamber, often called a secondary combustion chamber. Inefficient process of the post-combustion leads to high incomplete combustion losses and high emission of the CO to the atmosphere. It is possible to improve the combustion process by providing efficient mixing of the gas fuel and the oxidant, preventing rapid decrease of the temperature in the secondary combustion chamber and extending the time of the fuel presence in the combustion area.

2. Dynamics of changes of the CO emission during combustion proces in the biomass batch boiler

In case of the batch biomass boilers characterised by the simple construction, high emission of carbon monoxide is a significant problem, which currently is the goal of studies described in many papers. In [3], authors describe works devoted to the optimisation of the air manifold, which provides the primary and the secondary air to the gasification process, which occurs in the primary chamber of the boiler and post-combustion of the flammable products in the secondary chamber. Specifics of the combustion in the biomass batch boilers has been shown in [4]. Moreover, the process of the biomass combustion strongly depends on the type and size of fuel, specifics of device and the process conditions, which is described in [5, 6].

Fig. 1 presents the example result of the experimental test, performed on the installation of the 180 kW straw-fired boiler (1/4th of the nominal fuel load – about 40 kg). In the first 5 minutes the air fan efficiency was increased to 100% (0.18 m^3/s) and it was decreased to 0 after 70 minutes of the boiler operation. The water flow through the water jacket was constant (about 8 m^3/h). Temperature on water inlet to the water jacket was about 323K. Temperature distribution in the selected points of the primary and secondary combustion chamber, as well as the CO emission analyses have been performed.

The symbols of the sensors included on the chart legend correspond to the given locations of the measurements: DR2 – central point of the boiler door region, PR3 – the top of the secondary combustion chamber (outlet of the exhaust to the ash separator), TY – the bottom of the secondary combustion chamber (inlet of the CO to the region of the post-combustion). Through the first 5 minutes, the process of ignition occurs, in which the reactions are random. After the rapid growth of the temperature, the nominal process of the gasification (and combustion) takes a place to about 30th minute. Then the stage of the smoldering of the solid residues in the primary combustion chamber occurs till the end of the fuel burning cycle.

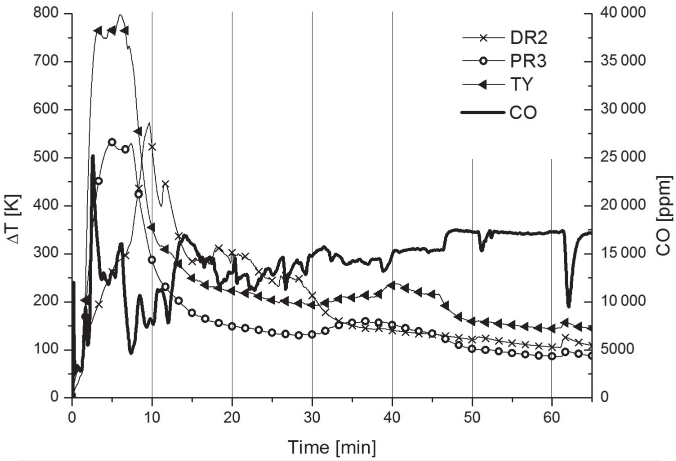

Fig. 1. Dynamics of the temperature variation in the primary and the secondary combustion chambers and the CO emission, recalculated to the 13% of the oxygen in the exhaust

To investigate the possibility of the reduction of CO emission during the whole process of the straw combustion, the numerical and experimental methods have been used simultaneously, to find a simple method of the post-combustion improvement and to evaluate usefulness of the numerical computations results in the optimisation process of the heating unit.

3. Optimization of the combustion process in the small biomass-fired boiler

Based on the result of the experimental tests partially presented in the previous chapter, the secondary air feeding system has been identified as ineffective. As a first step of the optimisation process, the numerical CFD (computational fluid dynamics) model of the CO post-combustion in the current state of the biomass boiler (Fig. 2a) has been developed.

To analyse the process of the CO post-combustion in cases of the current and modified design of the air feeding system, the commercial software ANSYS Workbench 15 has been applied. Spatial geometry of the secondary chamber has been developed in Autodesk Inventor 2015 software. It was decided, that it is justified to ignore the primary chamber, because the moment when the chamber is almost full of straw in the form of compressed blocks was considered. The geometry has been exported through the ANSYS DesignModeler to the ANSYS Meshing, where the discretization of the computational domain has been carried out. Total number of the elements was $1.3 \cdot 10^6$.

Because of non-homogeneous air distribution along the pipes of the air manifold, the primary and secondary air inlets have been set as an individual boundary conditions. The highest value of the mass flow was set for the central pipe, located on the symmetry plane of the geometry (Fig. 2b) and for the secondary air nozzles, 0.0237 kg/s and 0.0239 kg/s, respectively. The mass flow for other ducts oscillate around 0.0235 kg/s. The boundary conditions assumed for the CFD model are presented in Fig. 2.b, where the SAN is “secondary air nozzle” and PAN are “primary air nozzles”.

a) b)

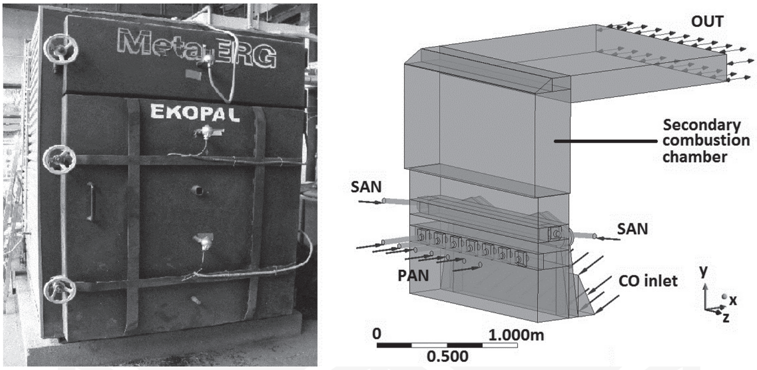

Fig. 2. Straw-fired boiler on the measurement stand (a) and the domain of the secondary combustion chamber (modified case) defined in the numerical model (b)

To simulate the chemical reaction of the O_2 and CO, the eddy dissipation model of combustion has been applied, which is based on the Arrenius equation. The *k*–ε model of turbulence has been applied, due to the lack of the inflation layer. ANSYS CFX solver, which is based on the finite volumes technique has been applied to perform the computations.

a) b)

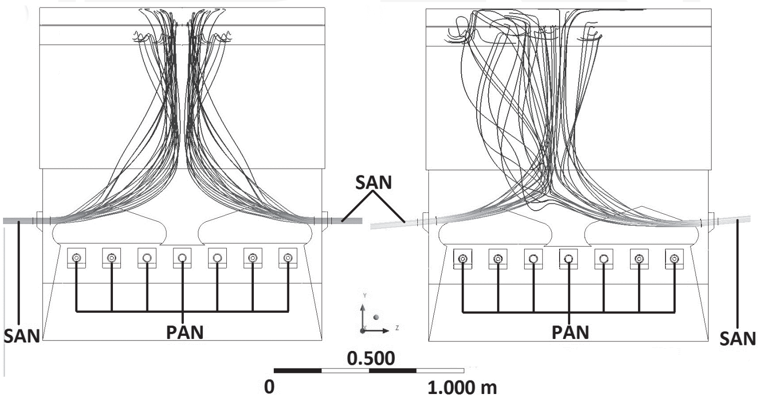

Fig. 3. Result of the numerical simulation of the secondary air fluxes in the secondary combustion chamber: a) current state of the heating unit, b) proposed modification of the secondary air nozzles

Due to the goal of study – comparison of the CO post-combustion in case of two different methods of the secondary air feeding, the steady state CFD model has been applied. Constant mass flux of the CO as an inlet boundary condition has been assumed (Fig. 2b). Fig. 3a presents the result of the computation in range of the secondary air fluxes in current state of the studied device. Due to the location of the nozzles opposite each other and moderate mass flow rates, the flow in the centre of the combustion chamber is laminar, which results in high concentration of the oxygen and CO in the exhaust.

It was found, that for the better degree of the O_2 and CO mixing, it is necessary to change the direction of the secondary air fluxes. It was decided, that the simplest solution to achieve higher efficiency of the reactants mixing and consequently of the post-combustion is to deflect nozzles. CFD simulation with deflection of the nozzles by 5° in horizontal and vertical axis has been carried out. The result of the modification is shown in Fig. 3b.

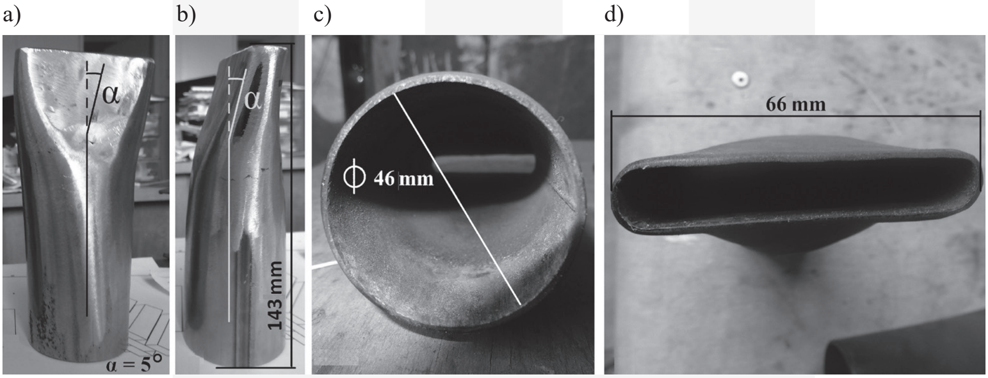

Fig. 4. Nozzles, which are responsible for deflection of the secondary air fluxes in the experiment

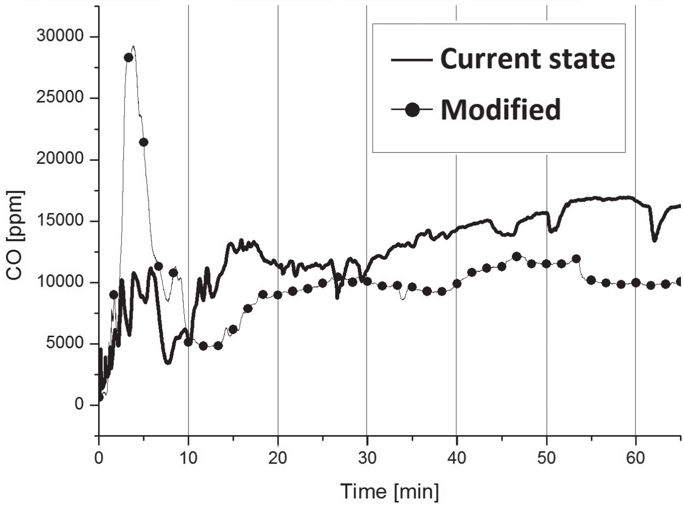

Fig. 5. Comparison of the averaged dynamics of the CO emission changes in case of the current state of the heating unit and after modification of the secondary air nozzles

In result of the nozzles deflection, 3.8% points of O_2 reduction and 2.3% points of CO_2 increase in the exhaust (with equal inlet CO mass flux) have been achieved in case of the CFD simulations. Based on the promising results of the computations, the deflected nozzles presented in Fig. 4 has been developed and applied as caps for the current secondary air ducts. Three series of the experimental tests have been carried out both for the base state of the boiler and for the deflected nozzles. Each series consisted of the preliminary combustion (warming up of the boiler) and proper experiment and they were conducted in the same conditions (fan efficiency, mass of the fuel etc.). The emission levels from experimental series for the first and second case of the secondary air feeding have been averaged and presented in Fig. 5. After the stage of ignition (to the 5th min. of the experiment), permanent effect of the CO emission reduction has been achieved, which was possible by intensification of the turbulences in the area of the post-combustion.

4. Conclusions

The process of biomass combustion in the batch boiler requires to provide efficient mixing of the gasification products and the oxidant. To achieve satisfying levels of the CO concentration in exhaust it is reasonable to apply deflected secondary air nozzles, which improve the flow turbulences, resulting in the higher efficiency of the chemical reactions. Designed configuration of the nozzles can be applied in form of the air ducts, instaled in the new-designed units, as well as in form of the caps, implemented in the existing heating units. In the second of the mentioned cases, modification is efficient and economically reasonable (cheap solution). The optimal angle of the deflection, as well as shape of the diffusors have to be determined, which will be achieved using CFD modeling as the next stage of the studies. Results of the computations will be compared with data from experiments, performed on the boiler with implemented solutions.

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